

ULTRALUMINOUS X-RAY SOURCES IN EXTERNAL GALAXIES

A.R. KING¹, M.B. DAVIES¹, M.J. WARD¹, G. FABBIANO² & M. ELVIS²*Draft version April 23, 2001*

ABSTRACT

We investigate models for the class of ultraluminous non-nuclear X-ray sources (ULXs) seen in a number of galaxies and probably associated with star-forming regions. Models where the X-ray emission is assumed to be isotropic run into several difficulties. In particular formation of sufficient numbers of the required ultramassive black-hole X-ray binaries is problematic, and the likely transient behaviour of the resulting systems is not in good accord with observation. The assumption of mild X-ray beaming suggests instead that ULXs may represent a shortlived but extremely common stage in the evolution of a wide class of X-ray binaries. The best candidate for this is the phase of thermal-timescale mass transfer inevitable in many intermediate and high-mass X-ray binaries. This in turn suggests a link with the Galactic microquasars. The short lifetimes of high-mass X-ray binaries would explain the association of ULXs with episodes of star formation. These considerations still allow the possibility that *individual* ULXs may contain extremely massive black holes.

Subject headings: accretion, accretion discs — binaries: close — X-rays: stars

1. INTRODUCTION

The existence in spiral galaxies of off-nuclear X-ray sources whose luminosities appear significantly larger than the Eddington limit for a $1M_{\odot}$ object has been known for some time (Fabbiano, 1989). These sources are distinct from the weak AGN present in many spiral galaxies known as LINERs (Ho et al. 1997), although in at least one case (M33, cf Dubus et al, 1997) they may be confused with AGN. Recently considerable effort has been devoted to interpreting the properties of these ‘ULXs’ (= ultra-luminous compact X-ray sources, e.g Makishima et al, 2000 and references therein). A key to understanding their nature may be that they appear to occur preferentially, although not exclusively, in regions of star formation (Zezas, Georgantopoulos & Ward 1999; Roberts and Warwick 2000, Fabbiano, Zezas & Murray, 2001). In this paper we investigate models for the ULXs.

Bright, non-nuclear X-ray point sources in galaxies divide into two groups: accreting neutron stars and black holes, and young supernova remnants. The luminosities of the first group, but not the second, are constrained by the Eddington limit:

$$L_X \lesssim L_{\text{Edd}} \simeq \frac{4\pi G M_1 m_p c}{\sigma_T} \simeq 1.3 \times 10^{38} m_1 \text{ erg s}^{-1}, \quad (1)$$

where σ_T is the Thomson cross-section and m_1 is the accretor mass M_1 in M_{\odot} . This constraint applies to *any* non-explosive source, whether powered by accretion or other means such as nuclear burning.

Evasions of the limit are possible, but rare. In the transient system A0538–66 a magnetic neutron star accretes from the wind of a Be-star companion. The system sometimes has super-Eddington luminosities $L_X \simeq 10^{39} \text{ erg s}^{-1}$ (White & Carpenter, 1978) but these may result from the reduction in the electron scattering cross-section below σ_T in the $\sim 10^{11} \text{ G}$ magnetic field of the neutron star per-

vading the accretion columns. Thus if we regard the observed variability of ULXs as ruling out the identification as supernova remnants, a straightforward interpretation as non-explosive sources requires black holes with masses $M_1 \gtrsim 50\text{--}100M_{\odot}$, accreting at rates which on occasion can exceed $\sim 10^{-6}M_{\odot} \text{ yr}^{-1}$. As we shall see, while individual ULXs could harbour such masses, there are major difficulties with such a picture as an explanation for the ULXs as a class. Accordingly we consider models in which the X-ray emission is assumed to be significantly beamed. In this case ULXs may correspond to a relatively shortlived but common epoch of the evolution of close intermediate- or high-mass X-ray binaries, perhaps the thermal-timescale mass transfer phase following the normal X-ray phase.

2. LUMINOSITIES, LIFETIMES, MASSES, BIRTHRATES

We first consider the restrictions placed by observation on accretion models for the ULXs. We assume that a compact object of mass M_1 accretes from a mass reservoir (e.g. a companion star) of mass M_2 . We denote the mean observed number of ULXs per galaxy as n , the beaming factor as b ($= \Omega/4\pi$, where Ω is the solid angle of emission), the duty cycle ($=$ time that the source is active as a fraction of its lifetime) as d , and define an ‘acceptance rate’ a as the ratio of mass accreted by M_1 to that lost by M_2 , i.e. the mean accretion rate $\dot{M}_1 = a(-\dot{M}_2)$. We further define L_{sph} as the apparent X-ray (assumed bolometric) luminosity of a source, given by the assumption of isotropic emission, and let $L_{40} = L_{\text{sph}}/10^{40} \text{ erg s}^{-1}$. From these definitions it follows that the luminosity

$$L = bL_{\text{sph}} = 10^{40} b L_{40} \text{ erg s}^{-1} \quad (2)$$

and the minimum accretor mass if the source is not to exceed the Eddington limit is

$$M_1 \gtrsim 10^2 b L_{40} M_{\odot}. \quad (3)$$

¹Department of Physics and Astronomy, University of Leicester, Leicester LE1 7RH, U.K.; ark@star.le.ac.uk

²Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138

The total number of such sources per galaxy is

$$N = \frac{n}{bd} \quad (4)$$

with a minimum mean accretion rate during active phases of

$$\dot{M}_{\text{active}} = \frac{\dot{M}_1}{d} = -\frac{\dot{M}_2 a}{d} > 10^{-6} b L_{40} \text{ M}_{\odot} \text{ yr}^{-1}. \quad (5)$$

The mass loss rate from M_2 is thus

$$-\dot{M}_2 > 10^{-6} \frac{bd}{a} L_{40} \text{ M}_{\odot} \text{ yr}^{-1}, \quad (6)$$

and the lifetime of a source is

$$\tau = -\frac{M_2}{\dot{M}_2} \lesssim 10^6 \frac{m_2 a}{bd L_{40}} \text{ yr}, \quad (7)$$

with $m_2 = M_2/M_{\odot}$, leading to a required birthrate per galaxy

$$B = \frac{N}{\tau} \gtrsim \frac{n}{bd} \cdot \frac{bd L_{40}}{10^6 m_2 a} = 10^{-6} \frac{n L_{40}}{m_2 a} \text{ yr}^{-1}. \quad (8)$$

It is important to note here that the required birthrate is independent of beaming (and duty cycle): the greater intrinsic source population N required by $bd < 1$ (cf eq. 4) is compensated by their longer lifetimes (cf eq. 7).

3. UNBEAMED MODELS

For an unbeamed model we set $b = 1$, and recover from (3) the requirement $M_1 \gtrsim 10^2 L_{40}$. We note immediately that some ingenuity is required (cf Makishima et al., 2000) to make these masses compatible with the characteristic observed X-ray temperatures 1–2 keV, whereas these are natural values for the lower masses we shall find below for beamed models. With $b = 1$ (5) gives $\dot{M}_{\text{active}} \gtrsim 10^{-6} L_{40} \text{ M}_{\odot} \text{ yr}^{-1}$. This effectively forces the mass reservoir to be a companion star; except for extremely high black hole masses $M_1 \gtrsim 3 \times 10^4 \text{ M}_{\odot}$, Bondi accretion from even a relatively dense part of the interstellar medium is inadequate, giving a rate

$$\dot{M}_{\text{Bondi}} \simeq 1 \times 10^{-11} \frac{m_{100}^2 (\rho/10^{-24} \text{ g cm}^{-3})}{u_{10}^2 + c_{10}^2} \text{ M}_{\odot} \text{ yr}^{-1} \quad (9)$$

where $m_{100} = M_1/100 \text{ M}_{\odot}$, ρ is the mass density of the ambient interstellar medium, and u_{10}, c_{10} are the relative speed of the hole and the local ISM, and the local ISM sound speed, both in units of 10 km s^{-1} . While individual ULXs might contain black holes of masses $M_1 \gtrsim 3 \times 10^4 \text{ M}_{\odot}$, it seems improbable that a galaxy like the Antennae should contain about 10 accreting examples. Unbeamed models for the ULX class thus have to invoke a class of extremely massive X-ray binaries. As we shall see, this may be a potential problem. Accepting that suitable binaries could in principle form, there are the usual constraints familiar from LMXB evolution (cf Kalogera & Webbink, 1996). Particularly important are (a) the binary must be wide enough that the progenitor of the compact star (here a $\sim 100 \text{ M}_{\odot}$ black hole) must be able to fit inside its Roche lobe (otherwise it will

provoke common-envelope evolution), and (b) the binary must be able to provide the inferred minimum accretion rate $\dot{M}_1 \sim 10^{-6} \text{ M}_{\odot} \text{ yr}^{-1}$. Constraint (a) immediately sets a scale, as main-sequence stars of masses $\gtrsim 100 \text{ M}_{\odot}$ have radii $\gtrsim 10^3 R_{\odot}$ (e.g. Stothers & Chin, 1999). Using Kepler's law, and assuming $M_1 \gg M_2$, this implies binary periods

$$P \gtrsim 1 m_{100}^{-0.5} \text{ yr}. \quad (10)$$

We can compare this with the critical period beyond which the accretion disc around the black hole cannot be thermally stable, and the system must therefore be transient. From King (2000) we find

$$P_{\text{crit}} \sim 4 m_{100}^{1/8} m_2^{1/8} \text{ d}. \quad (11)$$

We see that unbeamed ULXs must be transient. Hence the inferred $\dot{M}_1 \sim 10^{-6} \text{ M}_{\odot} \text{ yr}^{-1}$ now refers to the outburst state only: this is advantageous, as persistent mass transfer rates $-\dot{M}_2$ of this order would have been difficult to explain. To fill the Roche lobe in a binary with period given by (10) requires an extended star (note that the binary period essentially fixes the mean density of this star uniquely, cf e.g. Frank et al., 1992, Ch. 4). From the formulae of King (1988) (cf Ritter, 1999) we see that an evolved star with helium core mass $M_c \sim 0.4 - 0.5 \text{ M}_{\odot}$ will fill the Roche lobe, independently of the total donor mass $M_2 > M_c$. Mass transfer is driven by the nuclear expansion of the star, at the rate

$$-\dot{M}_2 \simeq 1 \times 10^{-7} P_{\text{yr}}^{0.93} m_2^{1.47} \text{ M}_{\odot} \text{ yr}^{-1} \quad (12)$$

where P_{yr} is the binary period in years (cf King, Kolb & Burderi, 1996, eq 7). Thus even a duty cycle d as long as 10% would yield mean accretion rates of the required order, i.e. $\dot{M}_1 = \dot{M}_{\text{active}} = \dot{M}_1 d^{-1} \sim 10^{-6} \text{ M}_{\odot} \text{ yr}^{-1}$ during outbursts.

However, applying the simple irradiated-disc theory of King & Ritter (1998) predicts that the accretion rate \dot{M}_{active} should decay linearly from its initial peak down to zero on a 10–20 yr timescale. This is not easily compatible with comparison of ROSAT and *Chandra* data. This may not be a crucial objection to this type of unbeamed model for ULXs; the theory of outbursts in large irradiated discs is complicated, even without adding further difficulties such as radiation-induced disc warping.

A more serious objection to unbeamed models is the one touched on above, namely that they require a $\sim 100 \text{ M}_{\odot}$ black hole to coexist in a binary with an evolved companion star. Mass loss from very massive stars with non-zero metallicity is usually thought to be so strong that the final black hole mass is much smaller than the initial stellar mass (see Baraffe, Heger & Woosley 2001 for a recent view, and Papaloizou 1973 for a possible objection). Assuming coeval formation of the two stars in the binary rules out a primordial origin for the black hole progenitor, and would thus require a progenitor with a mass $\gg 100 \text{ M}_{\odot}$. If the IMF within the stellar clusters is close to that of Salpeter, we conclude that the number of stars formed having masses $\geq 100 \text{ M}_{\odot}$ is a factor ~ 100 lower than the number of stars having initial masses $10 \leq m \leq 100 \text{ M}_{\odot}$. We would therefore expect X-ray binaries containing neutron stars and lower-mass black holes to outnumber markedly

those containing higher-mass black holes. The X-ray luminosity of the systems observed in the Antennae (Fabbiano, Zezas & Murray, 2001) contradicts this, assuming that all systems are unbeamed, although the number of low luminosity systems is not currently well known.

Alternatively, a $\sim 100M_\odot$ black hole may only recently have gained a new stellar partner. Such black holes may be produced within dense clusters through the merger of lower-mass black holes (see for example Lee 1993, 1995). Indeed this has been proposed as the origin of the moderate-mass black hole inferred to be present in the central regions of M82 (Matsushita et al 2000, Matsumoto et al. 2001, Kaaret et al., 2001). Although it is possible that a moderate-mass black hole produced in a central cluster of M82 has gained a stellar companion by some dynamical process (tidal capture or via an exchange encounter involving a binary, this scenerio is unlikely to work for the systems observed in the Antennae where the ULXs are observed to be strongly associated with the young star clusters which are located some distance from the galactic nuclei (Fabbiano, Zezas & Murray, 2001). Any massive BHs would therefore have to be formed within these stellar clusters and not the nuclear clusters. To produce moderate-mass black holes within a cluster via the successive merger of lower-mass objects, the potential well of the cluster has to be sufficiently deep to retain the black holes. This can be the case for the stellar cluster in the nucleus of a galaxy but is not true for globular clusters where the typical escape speed is far too low to retain black hole binaries as they are hardened via encounters. This has been suggested as the reason for the absence of black hole binary systems in globular clusters (Sigurdsson & Hernquist 1993, Kulkarni et al 1993).

A population of $\sim 100M_\odot$ black holes originating from a much earlier generation of effectively zero-metallicity stars seems unlikely to explain the ULXs observed in the Antennae (Fabbiano, Zezas & Murray, 2001) as these black holes would be distributed throughout the galactic halo and the probability of picking up stars from the young stellar clusters via dynamical encounters within the last $\sim 10^7$ years is extremely low.

4. BEAMED MODELS

Since unbeamed models run into difficulties because of the required black hole mass $\sim 100M_\odot$ and the need for a companion, we consider the effect of assuming that the observed X-rays are mildly beamed. The simplest candidate mechanism is the idea that the accretion disc around an accreting black hole has much lower scattering optical depth over a restricted range of solid angles (e.g. the rotational poles) than in other directions. Almost all the emitted X-rays would therefore emerge in these directions. A beaming factor $b \lesssim 0.1$ would bring the required minimum accretor mass (cf eqn 3) into the range $M_1 \lesssim 10M_\odot$ commonly found in dynamical measurements of X-ray binaries, particularly quiescent soft X-ray transients (e.g. Charles, 1998), while $b \lesssim 0.01$ would bring M_1 down to neutron-star values. In addition this kind of disc geometry, i.e. a thick disc with a central funnel, may actually radiate a total luminosity in excess of the Eddington limit (Jaroszynski, Abramowicz & Paczynski, 1980; Abramowicz, Calvani & Nobili, 1980). Thus such modest b -values

may allow quite large apparent luminosities for perfectly standard black-hole or neutron-star masses. The obvious implication is that beamed ULXs might represent some short-lived phase in the evolution of a large class of X-ray binaries: from eqn 7 we find $\tau \lesssim 10^7 m_2 a / (b/0.1) d$ yr.

A good candidate for such a phase is an episode of thermal-timescale mass transfer. These are extremely common, occurring when the donor has a radiative envelope and is either (a) somewhat more massive than the accretor, and/or (b) first fills its Roche lobe as it expands across the Hertzsprung gap. In general both cases give rise to highly super-Eddington mass transfer rates. Case (a) is unavoidable for example in any neutron-star binary with an intermediate-mass ($\sim 2 - 4M_\odot$ donor): King & Ritter (1999) and Podsiadlowski & Rappaport (2000) show that Cygnus X-2 is a survivor of such an episode, in which $-M_2$ reached values of order $\sim 10^{-6}M_\odot \text{ yr}^{-1}$ and the excess mass transfer is simply blown away from the system rather than resulting in common-envelope evolution (see also King & Begelman 1999, and Kolb et al., 2000). Case (b) requires only a reasonably wide binary separation after formation of the compact star, and clearly benefits from a large initial phase space. One of Case (a) or (b) is also the likely path for all high-mass X-ray binaries such as Cyg X-1 once the current wind-fed X-ray phase ends.

Until recently it has generally been assumed that thermal-timescale episodes are unobservable, as they are short, and without beaming X-rays could not emerge from the super-Eddington accretion flow at all. We investigate here the possibility that ULXs could be systems in this phase, where beaming allows us to see the X-rays.

The thermal-timescale mass transfer rate from a donor near the upper main sequence is roughly (cf King & Begelman, 1999)

$$-\dot{m}_2 \simeq 3 \times 10^{-8} m_2^{2.6} M_\odot \text{ yr}^{-1}. \quad (13)$$

Comparing with the Eddington accretion rate we can calculate an acceptance rate

$$a = 0.43 m_1 m_2^{-2.6} \quad (14)$$

and thus a lifetime (assuming $d = 1$)

$$\tau \lesssim 4.3 \times 10^6 (b/0.1)^{-1} L_{40}^{-1} m_1 m_2^{-1.6} \text{ yr} \quad (15)$$

and birthrate

$$B \gtrsim 2.3 \times 10^{-6} n(b/0.1) L_{40} m_1^{-1} m_2^{1.6} \text{ yr}^{-1} \quad (16)$$

per galaxy. In particular, for a system like Cyg X-2, which has $m_1 \simeq 1.4, m_2 \simeq 3M_\odot$ (King & Ritter, 1999; Podsiadlowski & Rappaport, 2000; Kolb et al., 2000) we get a required birthrate

$$B \gtrsim 1 \times 10^{-6} n(b/0.1) L_{40} \text{ yr}^{-1}. \quad (17)$$

We may compare this with the Galactic birthrate $\sim 10^{-6} - 10^{-7} \text{ yr}^{-1}$ deduced for Cyg X-2-like systems (King & Ritter, 1999; Podsiadlowski & Rappaport, 2000; Kolb et al., 2000). For a high-mass black-hole system like Cyg X-1 both m_1 and m_2 are probably significantly higher, raising B by as much as an order of magnitude. However the short X-ray lifetime $\sim 10^5 \text{ yr}$ of this X-ray phase requires a correspondingly high Galactic birthrate $\sim \text{few} \times 10^{-5} \text{ yr}^{-1}$,

again allowing a significant ULX population. X-ray binaries reach the thermal-timescale phase in a timescale comparable with the main-sequence lifetime of the donor. Thus ULXs descending from *high-mass* X-ray binaries would naturally be associated with a young stellar population, as required by observation.

A possible example of a ULX in the Galaxy is GRS 1915+105, where $L_x \sim 1 \times 10^{39}$ erg s $^{-1}$ (e.g. Belloni et al., 1997). As this is a microquasar, with radio jet axis at about 70° to the line of sight (see Mirabel & Rodriguez, 1999), only mild beaming $b \sim 0.6$ is possible, even assuming that we view the system at the edge of the X-ray beam. However this is indeed sufficient to reduce the luminosity to sub-Eddington values. Moreover such a geometrical alignment is quite reasonable, as it offers an explanation for the very unusual long-term behaviour of GRS 1915+105. The system was not detected in X-rays until 1992, since when it has remained persistently bright with only short interruptions. The usual explanation of this as an accretion disc instability, prolonged by self-irradiation by X-rays (cf King & Ritter, 1998) would require an implausibly large disc mass. An attractive alternative is that the X-ray light curve reflects slight changes in the X-ray beaming, which would have decreased enough in 1992 to allow us to see the X-rays.

5. CONCLUSIONS

We have considered models for the ULX class and reached the following conclusions.

- (i) Unbeamed models probably require a black hole of $M_1 \gtrsim 100M_\odot$ in ~ 1 yr binary orbit with an evolved donor star. Forming such a system presents considerable difficulties, and even then the likely transient behaviour of the accretion disc in such a wide system is hard to reconcile with observation. It is still possible that an *individual* ULX may contain a very massive black hole ($M_1 \gtrsim 3 \times 10^4 M_\odot$), perhaps accreting from the interstellar medium.
- (ii) The assumption of mild beaming ($b \sim 0.1 - 0.01$) reduces M_1 to values already observed for Galactic X-ray

binaries, and suggests that ULXs represent a shortlived phase of their evolution. The most likely candidate for this is the thermal-timescale mass transfer episode inevitable in a very wide class of intermediate- and high-mass X-ray binaries. This in turn suggests a link to the Galactic microquasars (cf King, 1998, quoted in Mirabel & Rodriguez, 1999). The short donor lifetime in high-mass X-ray binaries would explain why ULXs are associated with young stellar populations.

The major theoretical uncertainty for (ii) above is whether beaming is a natural consequence of high accretion rates. Only large numerical simulations can address this question. Perhaps encouragingly for this type of model, not only are the X-ray spectra fairly similar to those of Galactic black hole systems, Kubota et al (2001) observed X-ray spectral transitions typical of such source in two ULXs. The same type of spectral and timing variability has also been seen in the X-9 source in the M81 field (La Parola et al [2001]). There are several possible observational tests of these ideas. First, continued X-ray monitoring with a view to detecting possible changes in beaming geometry is clearly worthwhile. We note however that X-ray eclipses are unlikely in any beamed model, assuming that the X-ray beam axis is normal to the binary plane. Optical identifications of ULXs might allow at least two kinds of test: if the total X-ray luminosities really are as large as predicted if there is no beaming, one might expect to detect photionization nebulae around ULXs. If on the other hand ULXs are beamed, and thus of normal stellar mass, one might hope ultimately to detect a spectroscopic period (say 10's of days) in a ULX within the Local Group.

We thank Mike Garcia, Jim Pringle, Hans Ritter, Tim Roberts, Rashid Sunyaev and Pete Wheatley for discussions. MBD gratefully acknowledges the support of a University Research Fellowship from the Royal Society. Theoretical astrophysics research at Leicester is supported by a PPARC rolling grant. This work was supported in part by NASA contract NAS 8-39073 (CXC).

REFERENCES

- Abramowicz, M.A., Calvani, M., Nobili, L., 1980, ApJ, 242, 772
- Baraffe, I., Heger, A., Woosley, S.E., 2001, ApJ, in press (astro-ph/0009458)
- Belloni, T., Mendez, M., King, A. R., van der Klis, M., van Paradijs, J., 1997, ApJ, 488, 109
- Charles, P., 1998, in Theory of Black Hole Accretion Disks, edited by Marek A. Abramowicz, Gunnlaugur Björnsson, and James E. Pringle. Cambridge University Press, 1998., p.1
- Dubus, G., Charles, P.A., Long, K., Pasi, J., 1997, ApJ, 490, 47
- Fabbiano, G., 1989, ARA&A, 27, 87
- Fabbiano, G., Zezas, A., Murray, S.S., 2001, ApJ, submitted
- Frank, J., King, A.R., Raine, D.J., 1992, Accretion Power in Astrophysics, 2nd Edition, Cambridge University Press, Ch. 4)
- Ho, L., Filippenko, A.V., Sargent, W.L., Peng, C.Y., 1997, ApJS, 112, 391
- Jaroszynski, M., Abramowicz, M.A., Paczynski, B., 1980, Acta Astronomica 30, 1
- Kaaret, P., Prestwich, A.H., Zezas, A., Murray, S.S., Kim, D.W., Kilgard, R.E., Schlegel, E.M., Ward, M.J., 2001, MNRAS in press (astro-ph/0009211)
- Kalogera, V., Webbink, R.F., 1996, 458, 301
- King, A.R., 1988, QJRAS, 29, 1
- King, A.R., 2000, MNRAS, 315, 306
- King, A.R., Begelman, M.C., 1999, ApJ, 519, 169
- King, A.R., Kolb, U., Burderi, L., 1996, ApJ, 464, 127
- King, A.R., Ritter, H., 1998, MNRAS, 293, L42
- King, A.R., Ritter, H., 1999, MNRAS, 309, 253
- Kolb, U., Davies, M. B., King, A.R., Ritter, H., 2000, MNRAS 317, 438
- Kubota, A., Mizuno, T., Makishima, K., Fukazawa, Y., Kotoku, J., Ohnishi, T., Tashiro, M., 2001, ApJL, 547L, 119
- Kulkarni, S. R., Hut P., McMillan, S., 1993, Nat., 364, 421
- La Parola, V., Peres, G., Fabbiano, G., Kim, D.-W., Bocchino, F., 2001, ApJ, in press
- Lee, H.M., 1995, MNRAS, 272, 605
- Lee, M.H., 1993, ApJ, 418, 147
- Makishima, Z., Kubota, A., Mizuno, T., Ohnishi, T., Tashiro, M., Aruga, Y., Asai, K., Dotani, K., Mitsuda, K., Ueda, Y., Uno, S., Yamaoka, K., Ebisawa, K., Kohmura, Y., Okada, K., 2000, ApJ, 535, 632
- Matsumoto, H., Tsuru, T. G., Koyama, K., Awaki, H., Canizares, C. R., Kawai, N., Matsushita, S., Kawabe, R., 2001, ApJL, 547, L25
- Matsushita, S., Kawabe, R., Matsumoto, H., Tsuru, T., Kohno, K., Morita, K., Okumura, S. K., Vila-Vilaro, B., 2000, ApJ, 545, 107
- Mirabel, I.F., Rodriguez, L.F., 1999, ARA&A, 37, 409
- Orosz, J., et al, 2001, ApJ, in press
- Papaloizou, J.C.B., 1973, MNRAS, 162, 143
- Podsiadlowski, Ph., Rappaport, S.A., 2000, ApJ 529, 946
- Ritter, H., 1999, MNRAS, 309, 360
- Roberts, T., Warwick, R., 2000, MNRAS, 315, 98
- Sigurdsson S., Hernquist, L., 1993, Nat., 364, 423
- Stothers, R.B., Chin, C.W., 1999, ApJ, 522, 960
- White, N.E., Carpenter, G.F., 1978, MNRAS, 183, 11P
- Zezas, A., Georgantopoulos, I., Ward, M.J., 1999, MNRAS, 308, 302